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EFFECT OF SHOCK PRECURSOR HEATING ON RADIATIVE FLUX TO BLUNT BODIES

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Prepared by
LOCKHEED MISSILES & SPACE COMPANY
Palo Alto, Calif.
for Ames Research Center

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NOMENCLATURE

h	static enthalpy
H	total enthalpy
$h\nu$	photon energy
q_R	radiation flux
R	universal perfect gas constant
R_B	nose radius
T	temperature
Γ	radiation loss parameter
ρ	density

Subscripts

∞	free stream
S	shock
W	body surface

Superscripts

$'$	after precursor heating
$-$	limited spectral region

Section 1
INTRODUCTION

Radiant energy, transported out of the shock layer of a blunt body traveling at high speeds, will reduce the total enthalpy in the inviscid region behind the shock wave. Absorption of this radiation by the free-stream air ahead of the shock reduces the amount of energy lost from the shock layer by raising the enthalpy and temperature of the free-stream air. However, it is only that energy absorbed in a distance fairly close to the body that will be convected back into the shock layer. The purpose of this study is to determine, quantitatively, the level of precursor absorption and its resultant effect on the surface radiative heating.

Previous results have shown that, at entry velocities on the order of 35,000 fps at 200,000 ft altitude, the shock layer temperature behind the shock is low and the resultant radiant energy loss is of negligible importance in reducing the total enthalpy. However, at an entry velocity of 65,000 fps at the same altitude, radiant energy transport from the shock layer ("radiation cooling") strongly influences the enthalpy distribution and hence precursor heating may be important.

An exact treatment of the precursor heating problem is quite difficult as it introduces an additional coupling to the shock layer calculation. The radiated energy that is absorbed by the free stream air alters the enthalpy profile ahead of the shock. The resultant increased enthalpy just in front of the shock changes the jump condition across the shock and alters the enthalpy profile behind the shock. This, in turn, affects the emergent radiative flux at the shock front and the absorption by the free stream air fully couples the profiles on both sides of the shock.

A simplified, uncoupled analysis is used herein to determine when precursor effects can be neglected or handled as a first order correction. This analysis neglects the change in the enthalpy profiles within the shock layer resulting from precursor heating.

Two models are used for the absorption properties of the cold free-stream air which give a conservative and liberal estimate, respectively, for the reabsorbed energy. The effect of increased absorption due to the higher temperatures of the free-stream air induced by precursor heating is included in the liberal estimate model.

Section 2

METHOD OF ANALYSIS

2.1 ONE-DIMENSIONAL HEATING MODEL

The following simplified, uncoupled calculation is used to determine when the precursor heating effect is important. The radiative flux at the shock is obtained from an enthalpy profile predicted by a solution that neglects radiation loss. A one-dimensional heating model is used which assumes that only radiation that is absorbed within a distance roughly equal to the shock layer thickness will be convected into the shock layer. Since the body radius is much greater than the shock layer thickness, the use of this representation for the heating is justified. The absorption properties of cold air are used to determine the frequency range where such a one-dimensional model will be valid.

The one-dimensional energy equation for the air upstream of the shock is integrated from the shock out to infinity yielding

$$\frac{h'_\infty}{H_\infty} - \frac{h_\infty}{H_\infty} = \frac{(\overline{q_R})_S}{\frac{1}{2}\rho_\infty U_\infty^3} \tag{1}$$

where h'_∞ and h_∞ are the enthalpies of the heated and cold free-stream air, respectively, H_∞ is the total enthalpy of the free-stream flow (taken to equal $1/2\ U_\infty^2$), $\rho_\infty U_\infty$ is the mass flux of air passing through the shock and $(\overline{q_R})_S$ is that part of the radiative flux emergent from the shock which is absorbed upstream of the shock. With the use of thermodynamic data (Ref. 1), the temperature of the heated air can be determined from h'_∞. The consequence of the higher temperature on the absorption properties of air is discussed in Section 2.3.

Energy loss from the shock layer reduces the surface radiative heat flux from its adiabatic value. The reduction in surface radiative heat flux has has been correlated through the use of a radiation loss parameter which is defined by

$$\Gamma \equiv \frac{(q_R)_S + (q_R)_W}{\frac{1}{2}\rho_\infty U_\infty^3} \tag{2}$$

where q_R is the radiative flux based on a shock layer solution without radiation loss and the subscripts S and W refer to the shock and body surface, respectively. Figure 1 shows results for this reduction as obtained from the non-grey radiative coupled viscous shock layer calculations of Ref. 2 as well as the unpublished calculations by Hoshizaki.* Note that since a viscous shock layer analysis was used, $(q_R)_S$ is not equal to $(q_R)_W$ even for the no radiation-loss case.

The reabsorbed energy convected back into the shock layer reduces the value of Γ by the amount

$$\Delta\Gamma = \frac{(\overline{q_R})_S}{\frac{1}{2}\rho_\infty U_\infty^3} \tag{3}$$

The effect of a change in Γ, resulting from precursor heating then can be related to a change in surface radiative heat flux by using the data of Fig. 1.

2.2 EMERGENT FLUX DETERMINATION

Based on detailed calculations by the VISC computer code, which solves the radiation coupled flow field, the spectral radiation emergent from the shock layer at the stagnation point is shown in Figs. 2, 3, 4, and 5. For each of the flight velocities considered, the free-stream density is that of air at 200,000 ft and the shock layer solution is for a spherical body with a

*"Third Meeting on Interdisciplinary Aspects of Radiation Transfer; Radiation Coupled Flows," Feb 23-24, 1967, Lockheed Palo Alto Research Laboratory (proceedings unpublished).

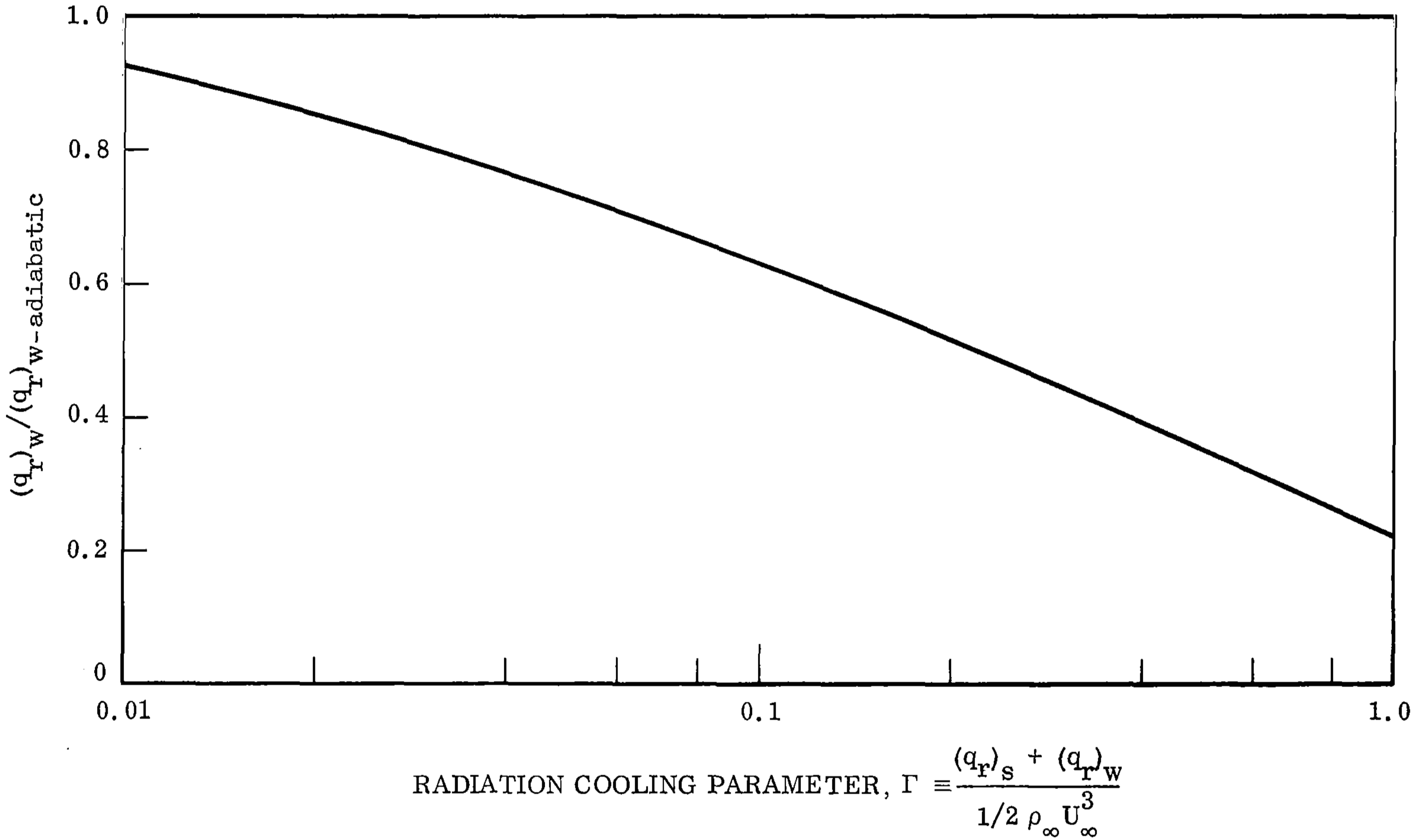

Fig. 1 Stagnation Point Radiation Flux

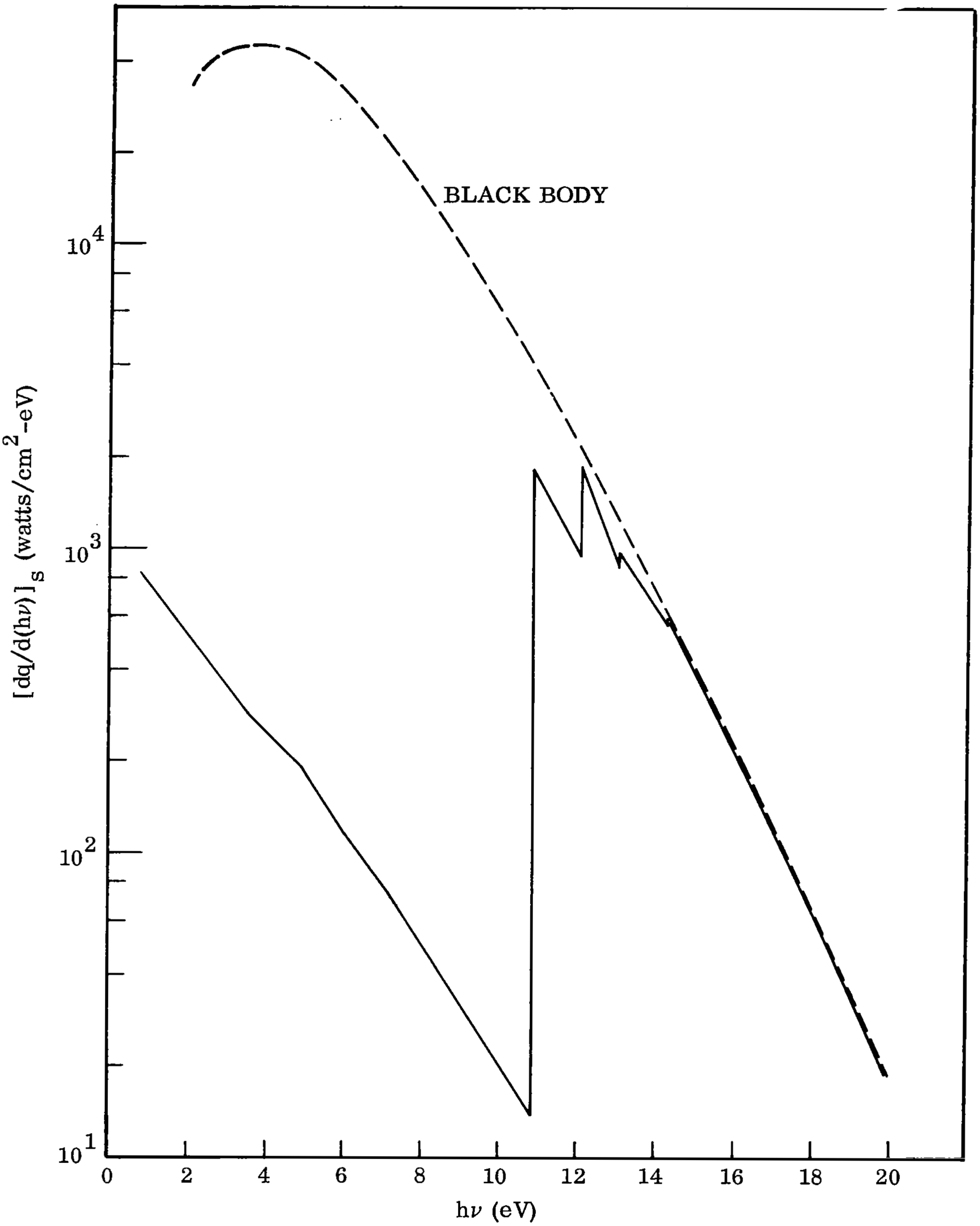

Fig. 2 Emergent Radiation From Shock U_∞ = 50,000 ft/sec; Altitude = 200,000 ft; T_s = 14,750°K; R_B = 5.0 ft

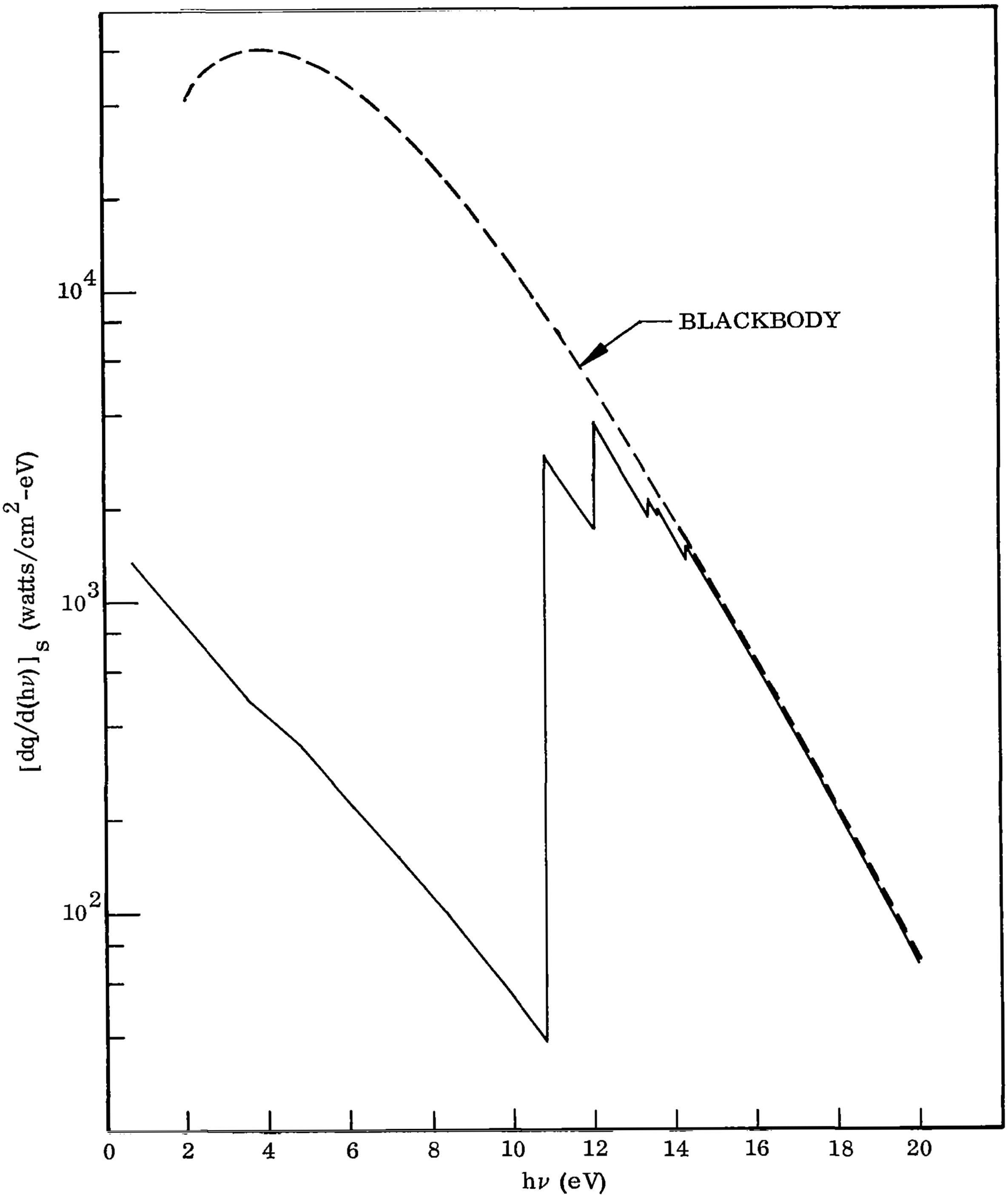

Fig. 3 Emergent Radiation From Shock U_∞ = 55,000 ft/sec; Altitude = 200,000 ft; T_s = 16,150°K, R_B = 5.0 ft

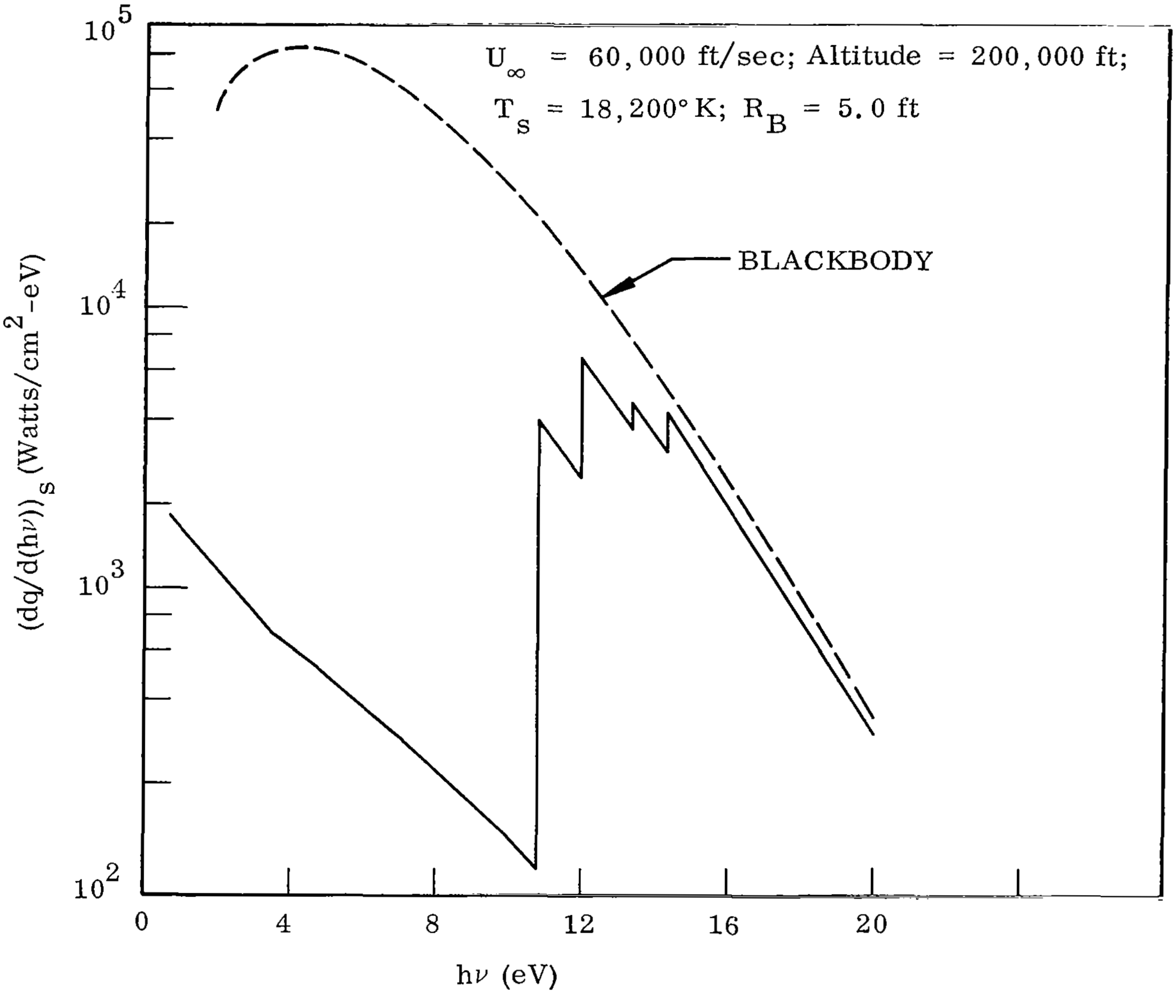

Fig. 4 Emergent Radiation From Shock

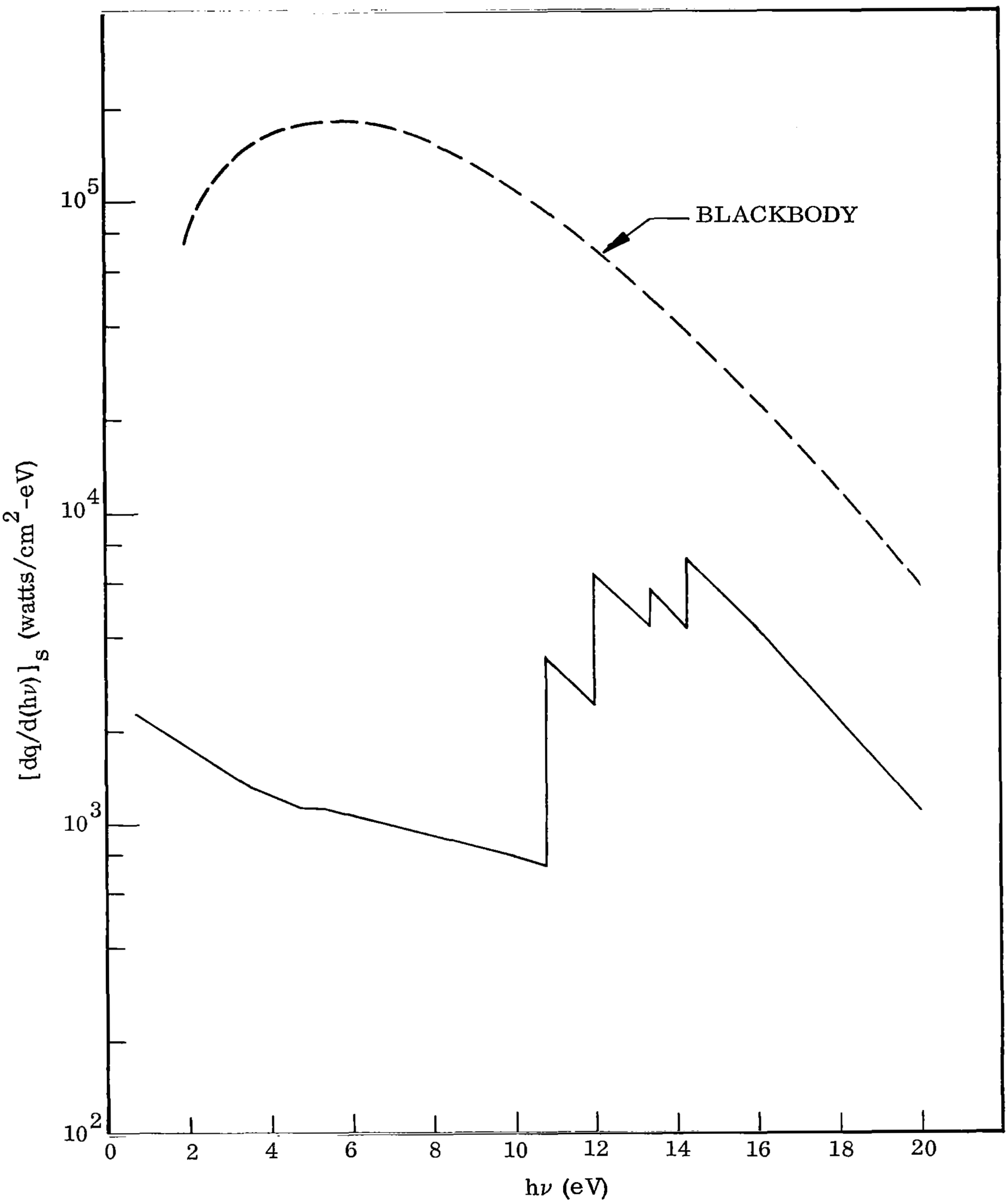

Fig. 5 Emergent Radiation From Shock $U_\infty = 65,000$ ft/sec; Altitude = 200,000 ft; $T_s = 23,350°K$; $R_B = 5.0$ ft

5.0 ft nose radius. Only continuum contributions were considered in determining the emergent radiative flux. The consequence of neglecting the line emission is discussed in the following section.

2.3 COLD AIR ABSORPTION MODELS

The one-dimensional model assumes that only the absorbed radiation of photons having a mean free path of about the shock layer thickness are recovered by convection back into the shock layer. For frequencies where the photon mean free paths are larger than the characteristic body dimension, cold air can be considered to be transparent as far as precursor effects are considered, since the absorbed radiation would still be lost from the shock layer.

The frequency ranges for significant cold air absorption are determined by an examination of spectral absorption coefficient data. Data reported by Churchill et al. (Ref. 3) show that all the energy radiated in the visible and infrared portions of the spectrum (i.e., $h\nu < 6.5$ eV) would be lost. Cold air absorbs in the 6.5 to 9.5 eV range of the ultraviolet due to the O_2 Schumann-Runge continuum and band system (Ref. 3). However, the energy absorbed in this range is neglected since reference to Figs. 2 through 5 indicates that very little continuum energy (several percent) is emitted at these frequencies.

To judge the effect of neglecting the line energy, an isothermal calculation which included lines was performed. A temperature of $18,000^{\circ}K$ and a pressure of 1 atm (conditions characteristic of a velocity of 60,000 ft/sec at 200,000 ft altitude) was used for this calculation. Most of the line energy is transported at frequencies less than 12.1 eV and in the 6.5 to 9.5 eV range amounted to 4.4×10^3 W/cm^2. In the other region where cold air absorbs significantly, i.e., $h\nu > 12.1$ eV, the shock emission is due primarily to the continuum and is 2.0×10^4 W/cm^2. Comparison of these two values indicates that in the spectral ranges where cold air absorbs, less than 25% of that energy is carried in lines. This 25% neglection results in an underestimation of $\Delta\Gamma$, [cf. Eq. (3)] by this amount. Reference to Fig. 1 indicates that a 25% error in $\Delta\Gamma$ would lead to a much lesser effect on the change in surface radiative heat flux (< 10%).

Only in the vacuum ultraviolet, where most of the shock emission occurs, is absorption in the cold air significant. Detailed absorption coefficients for N_2 and O_2 in the vacuum ultraviolet have been reported by Sullivan and Holland (Ref. 4). These data, which show a complicated band structure superimposed on a continuum background, have been used to estimate effective photon mean free paths. Photoionization of O_2 results in absorption at frequencies greater than 12.1 eV. The superimposed band structure on the O_2 continuum shows a wide variation in absorption coefficient leaving the effective absorption level open to question. Due to the photoionization of nitrogen molecules, air absorbs strongly at frequencies having an energy greater than 15.6 eV. The nitrogen molecule also has a multitude of narrow molecular bands starting at 12.4 eV. Viewed in the large, however, the absorption coefficient of N_2 is quite small until the photoionization continua is reached at 15.6 eV. An estimate of an effective photon mean free path at 200,000 ft altitude in the frequency range of 15.6 to 20.0 eV is 0.16 ft for N_2 absorption and 0.64 ft for O_2 absorption. The shock layer thicknesses at the flight conditions noted in Figs. 2 through 5 are about 0.20 ft.

Two estimates for the absorption properties of cold air are used. One includes the photoionization of both the oxygen and nitrogen molecules; this is a fairly liberal estimate for the reabsorbed energy (Model A). The other one considers the photoionization of only nitrogen molecules and is a somewhat conservative estimate for the reabsorbed energy (Model B).

One of the effects of precursor radiation is to heat the unshocked air to higher temperatures where the cold air absorption model may no longer be valid. Even at increased temperatures, air in the lower frequency portion of the spectrum ($h\nu$ < 6.5 eV) will remain optically thin (Ref. 3). However, the increased preshock air temperature may significantly increase the absorption properties of the air in the vacuum ultraviolet. The net effect of this rise in temperature would be to favor the results obtained using the liberal estimate model. It is recalled that this model allows for complete absorption of almost all the radiation in the vacuum ultraviolet portion of the spectrum.

2.4 RESULTS

The decrease in radiation loss parameter is evaluated using Eq. (3) along with the data of Figs. 2 through 5. This calculation is performed for the two different cold air absorption models: Model A, which assumes that the cold air absorbs all the energy emitted in the frequency range $h\nu > 12.1$ eV, and Model B, which assumes that the cold air absorbs at frequencies greater than $h\nu > 15.6$ eV. The band of results which comes from using the two models is shown in Fig. 6. The resulting correction to the radiation loss parameter is depicted in Fig. 7. As was mentioned previously, the temperature of the preheated air could be a factor in determining which model is a better representation. Figures 8 and 9 give the enthalpy and temperature, respectively, of the preheated air. Once again, these values result from the two absorption models.

The decrease in stagnation point radiative flux resulting from energy loss in the shock layer is presented in Fig. 10. For the case of $U_\infty = 50{,}000$ fps, inspection of Fig. 7 shows $\Gamma = 0.22$ and the surface flux reduction obtained from Fig. 1 is $(q_R)_W/(q_R)_{W\text{-adiabatic}} = 0.5$. Using the two estimates, respectively, for the $\Delta\Gamma$ value, the corrected values of surface flux reduction are 0.51 for Model B and 0.56 for Model A. This is either a 2 or 12% change in the surface radiative flux depending upon whether the conservative or liberal estimate is used. Calculations at $U_\infty = 55{,}000$ fps give a 3 to 15% change, at $U_\infty = 60{,}000$ fps give a 6 to 25% change, and at $U_\infty = 65{,}000$ fps give a 10 to 30% change. For the highest velocity, $U_\infty = 65{,}000$ fps, the $\Delta\Gamma$ value ranges from 0.09 to 0.24. The complete extent of flux corrections is given in Fig. 10.

To the authors' knowledge, the only other investigation of the effect of precursor heating on surface radiative flux is the work of Yoshikawa (Ref. 5). In contrast to our uncoupled analysis, Yoshikawa treats the fully-coupled problem accounting for the effects of an increase in enthalpy ahead of the shock on the shock layer profile. However, Yoshikawa uses a grey-gas treatment of the radiative transfer and, furthermore, assumes a linear relationship between the Planck emissive power (σT^4) and enthalpy functions. On the other hand, our treatment employs a full spectral calculation of the shock layer radiative fluxes and exact enthalpy-temperature relations. A comparison of the reduction in surface radiative flux due to radiative cooling (without precursor effects) between our calculations as given in Fig. 1 and analogous results given by Yoshikawa shows significant differences. For example, at a value of $\Gamma = 0.1$ (for shock layer pressures on the order of 1 atm) Yoshikawa shows a surface flux reduction to 0.80 of the adiabatic value, while our value from Fig. 1 for $\Gamma = 0.1$ and roughly similar shock layer thermodynamic conditions shows a reduction to 0.62 of the adiabatic value. Because of these differences, which result from the non-grey nature of the absorption processes within the shock layer when radiative cooling is considered, a comparison of the effect of precursor heating on the surface flux between Yoshikawa and ourselves is not valid.

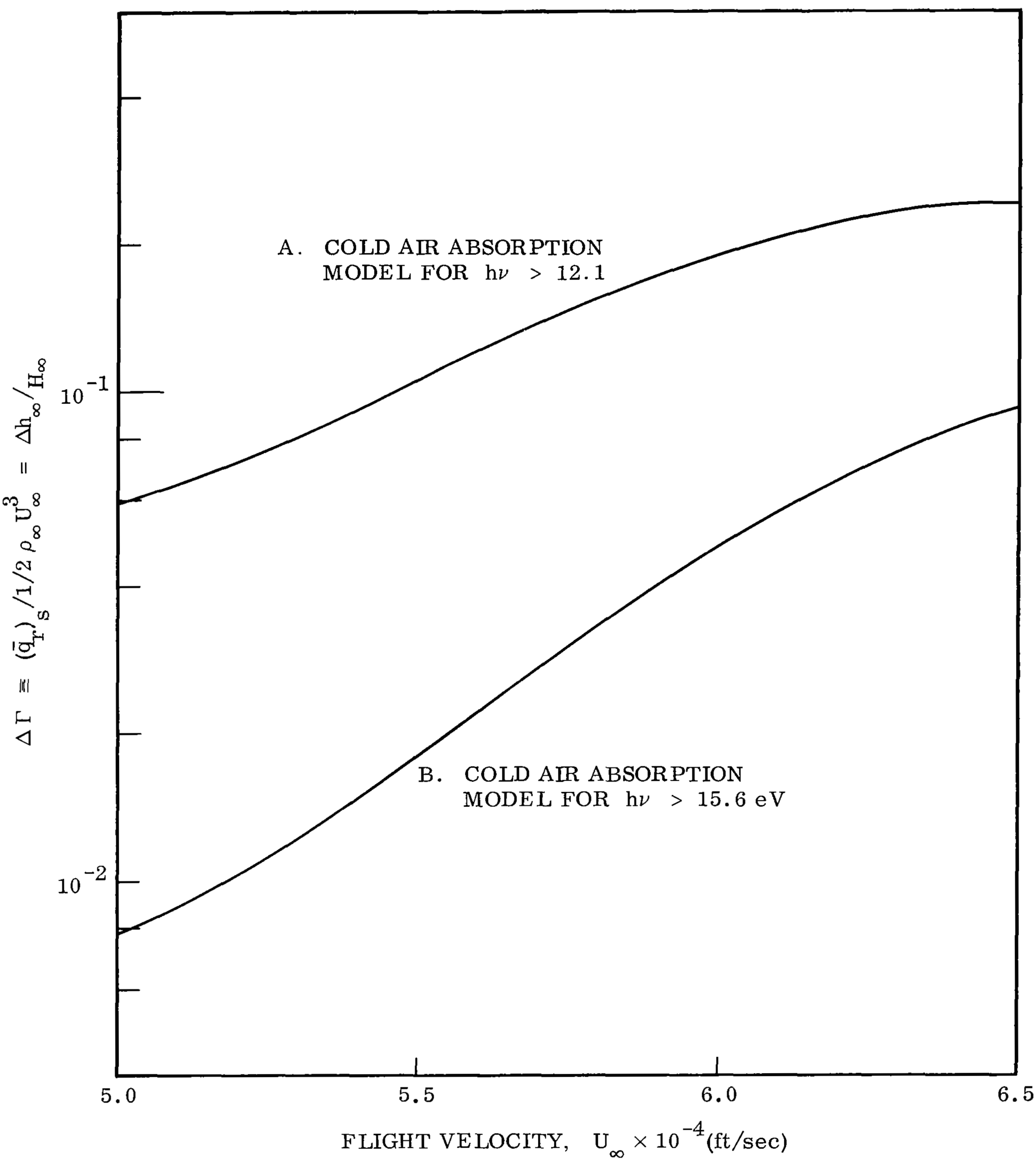

Fig. 6 Decrease in Radiation Loss Parameter Altitude = 200, 000 ft; R_B = 5.0 ft

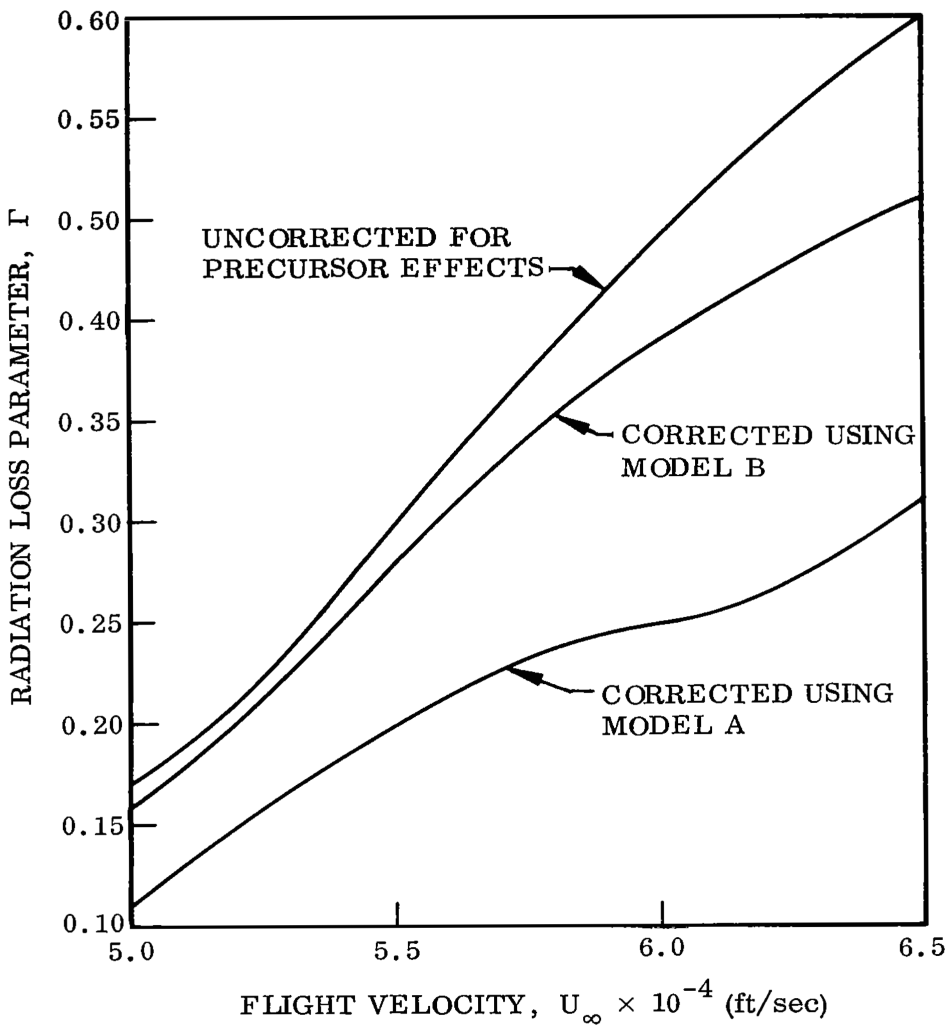

Fig. 7 Radiation Loss Parameter Altitude = 200,000 ft; R_B = 5.0 FT

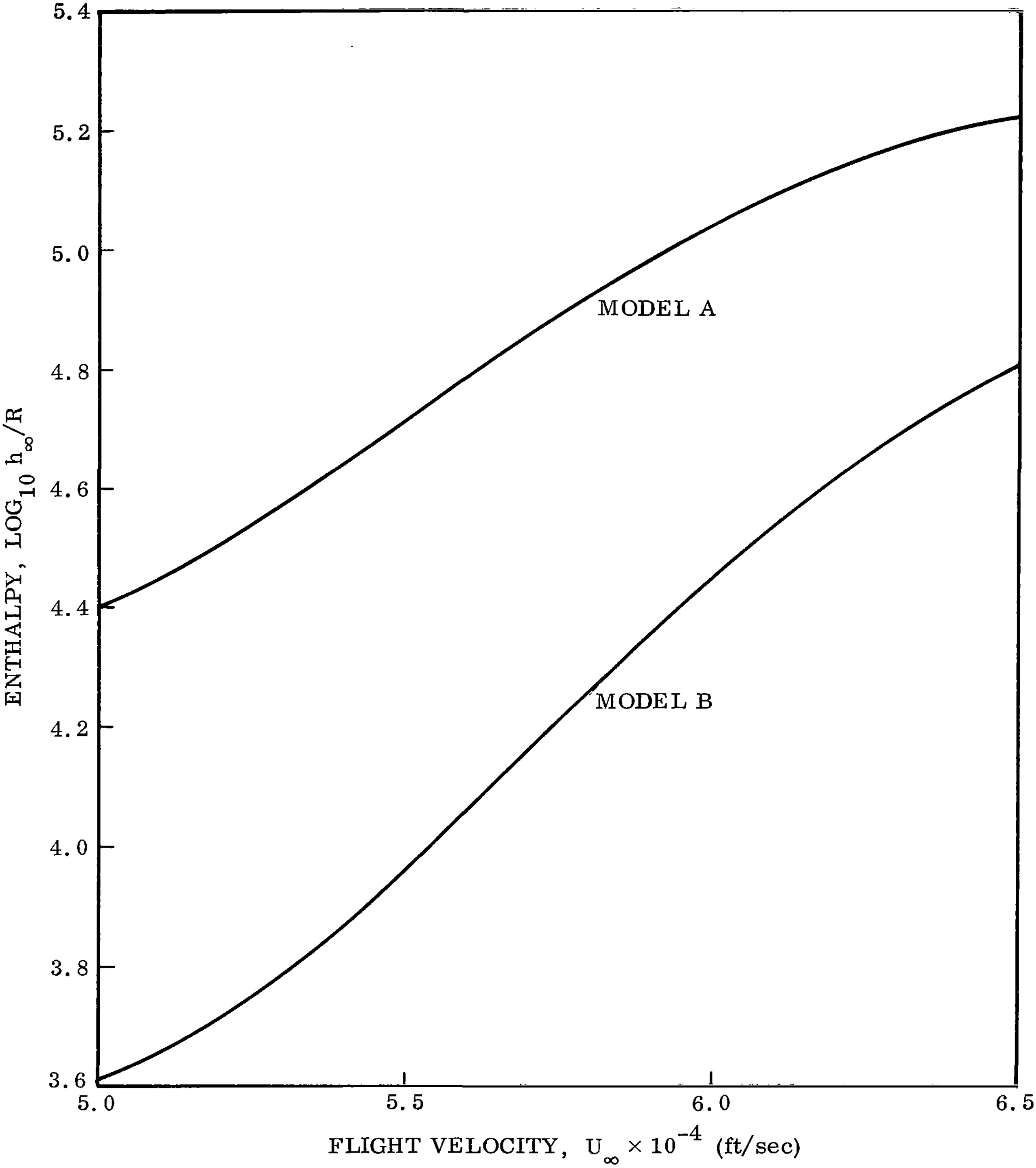

Fig. 8 Enthalpy of the Air in Front of the Shock Due to Precursor Heating
Altitude = 200,000 ft; R_B = 5.0 ft

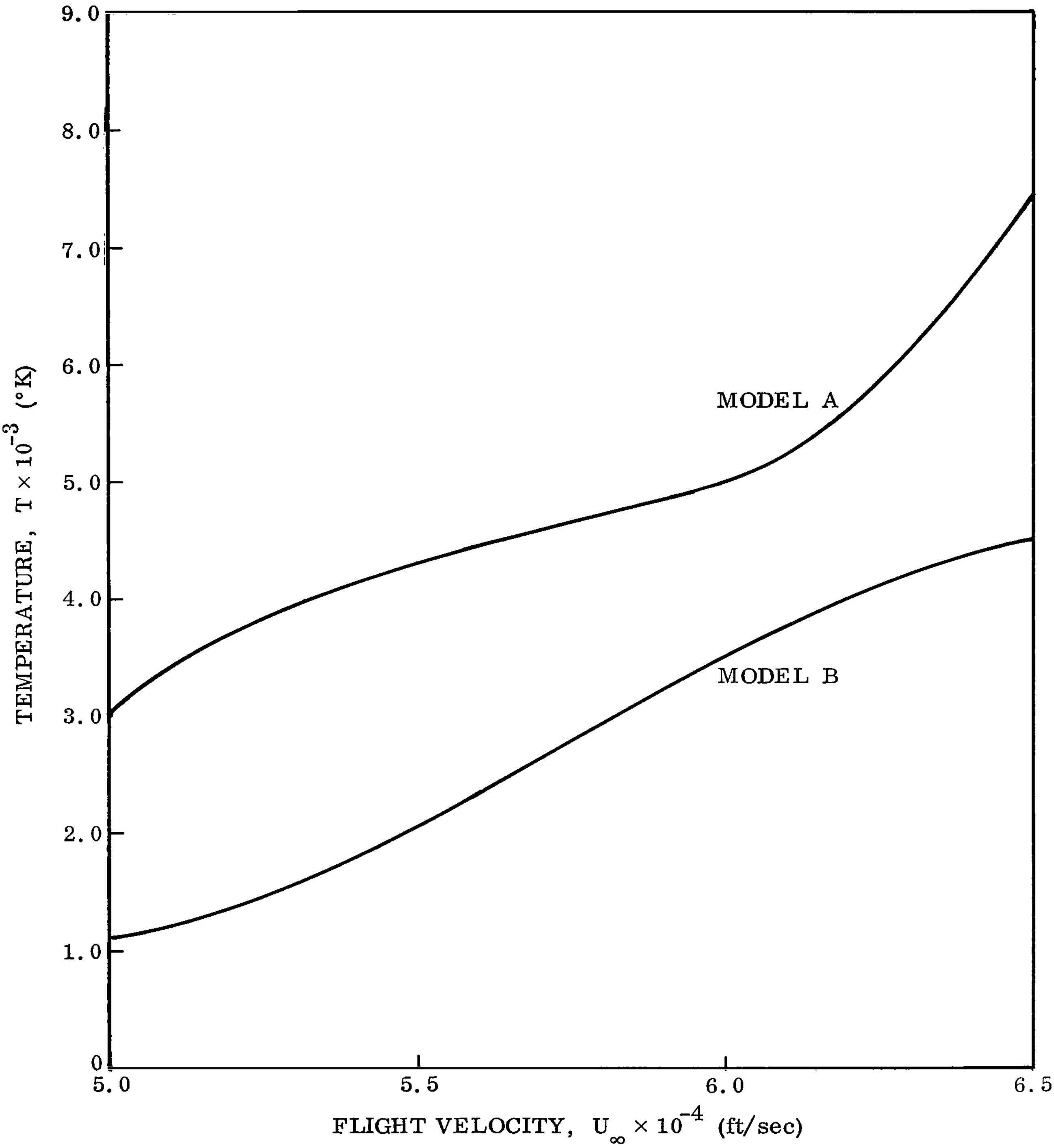

Fig. 9 Temperature of the Air in Front of the Shock Due to Precursor Heating
Altitude = 200,000 ft; R_B = 5.0 ft

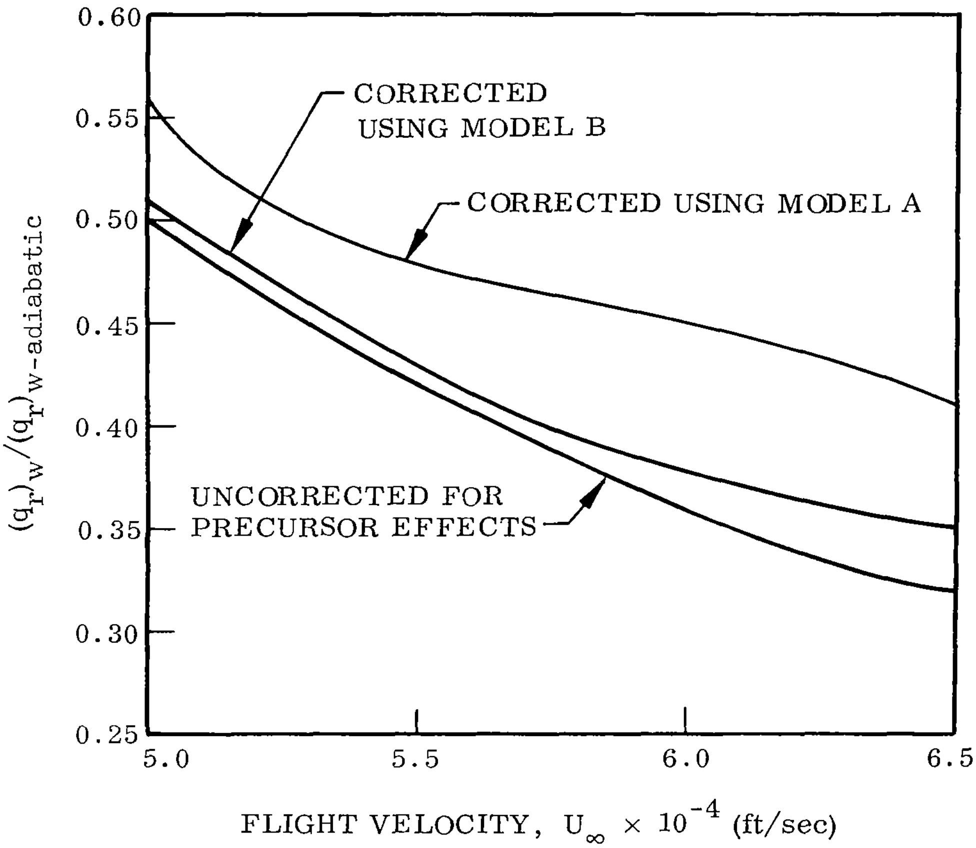

Fig. 10 Stagnation Point Radiation Flux With Radiation Cooling
Altitude = 200,000 ft; R_B = 5.0 ft

Section 3
CONCLUSIONS

A solution using a one-dimensional heating representation is used to determine the precursor heating correction to the surface flux. Based on these results, one can judge when a fully coupled radiative-gasdynamic flow analysis is needed. The conservative absorption model predicts only a 10% effect at $U_\infty = 65{,}000$ fps on the surface radiative heat flux. A correction of this order is not considered to be sufficiently important to justify a detailed coupled solution. When the cold air is preheated substantially, the absorption resulting from this model may be underestimated. A liberal absorption model is considered and indicates that at a velocity of 60,000 fps the correction to surface radiative flux would amount to 25%.

The true coupling effect of the precursor heating probably lies somewhere between the results produced by the two absorption models. The conclusion is reached that for velocities less than 60,000 fps precursor heating effects are relatively unimportant in determining the radiative flux reaching the body surface. At velocities greater than 60,000 fps the amount of energy loss from the shock layer and a resultant precursor heating correction is felt to be sufficiently large to justify a more detailed analysis.